MULTIPLE BEAM INTERVAL SCANNER

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SYLVANIA ELECTRONIC SYSTEMS
Government Systems Management
for GENERAL TELEPHONE & ELECTRONICS

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MULTIPLE BEAM INTERVAL SCANNER

Francis J. LaRussa

SYLVANIA ELECTRONIC SYSTEMS – EAST
SYLVANIA ELECTRONIC SYSTEMS
A Division of Sylvania Electric Products Inc.
100 First Ave., Waltham, Mass. 02154

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INTRODUCTION

It is generally recognized that the requirements for increasing the range, accuracy, and resolution of radar systems have gradually caused the size of antenna systems to increase correspondingly. The trend to larger apertures for both search and tracking radar antennas has indeed improved radar performance in these areas, but it has also aggravated the problems associated with the need for higher data rates required in the detection and tracking of high speed targets. As the size of a conventional reflector type of antenna is increased to produce a narrower beam, the speed with which it can scan a particular sector is decreased. The principal reason for the resulting slower scan rates is the mechanical problem of moving a large antenna. The need for large two-axes servo drive systems whose accuracy is compatible with the beamwidths involved, further compounds the mechanical problem. Since the larger antenna produces a narrower beam, it requires more traversals in the search mode to scan a particular sector in space. This increase in total distance traveled by the antenna, coupled with the slower rate at which the antenna travels (scan rate), is apt to render the radar ineffectual in detecting fast targets.

Of the possible solutions to this problem of increased range and accuracy, compatible with the high data rates required, the phased array appears to be the most versatile solution. However, the complexity and cost of the phased array precludes it from almost all but the most sophisticated of systems. A technique which solves the problem of maintaining a high data rate for large reflector type of antennas has been the subject of the MUBIS research program at Sylvania. MUBIS is an acronym which stands for Multiple Beam Interval Scanner. In the MUBIS technique a number of separate beams are generated and independently scanned using a single line source fed by a wide angle two-dimensional constrained lens. A theoretical discussion of the lens design is given in Reference 1. The problems encountered in the design of an actual antenna system and also the experimental results obtained on the program at Sylvania are described in Reference 2.

The MUBIS technique obviates some of the difficulties caused by the advent of large reflector antennas. The use of a wide angle lens has the advantage over an equivalent reflector antenna in that a large number of inputs can be provided along the focal arc to generate a multiplicity of independent non-overlapping beams. This allows a sector of space which is under surveillance by the antenna to be divided into a number of subsectors each of which can be simultaneously scanned more rapidly. The use of organ pipe scanners to feed these multiple inputs further increases the data rate since these devices can be rotated at high speeds.

The wide angle capabilities of the lens have been demonstrated experimentally. A sector of about ±36 degrees from broadside was scanned from a fixed line source and it appears theoretically possible that this sector can be increased appreciably. The ability to scan a narrow beam in one plane over such a wide angular sector using a fixed antenna

partly solves the mechanical problem by eliminating one axis of rotation. Possible antenna configurations using the MUBIS lens technique will be discussed in this report. They are deferred at this point since it is desirable to present additional background material before discussing them. However, this technique does have definite potential in helping to overcome some of the problems arising as a consequence of the need for larger antennas.

SECTION 1

THE CONSTRAINED LENS

Before investigating the possibilities of the MUBIS techniques, it is necessary to discuss the lens briefly, and also to consider its advantages over other antenna systems capable of performing similar functions. The lens, which enables the use of multiple inputs and permits wide angular coverage in one plane, is a two-dimensional constrained lens having a straight front surface suitable for use with a line source. Figure 1-1 is a schematic representation of the lens. It consists of a parallel plate transmission line which guides the energy appearing at the focal arc to the rear lens surface, Σ_1. Coaxial cables, connected to probes which lie along this surface, conduct the energy from the parallel plate region to the line of radiators which form the straight front surface, Σ_2, of the lens. These cables are the "constraining" elements of the lens since energy impinging on a particular point on the surface, Σ_1, is "constrained" to follow the same path through a particular cable to the surface, Σ_2, regardless of the angle at which this energy strikes the surface. In this respect, the "constrained" lens differs from the usual dielectric lens in which Snell's Law applies and the path length through the lens is a function of the angle of incidence. The lens is basically a broad band device because it is calculated on the basis of geometric optics and also because both the parallel plate transmission line and the coaxial cables, which constitute the lens elements, operate in the TEM mode.

The use of a parallel plate lens for scanning is not novel, but because of the difficulties involved in fabrication or in bandwidth, it has not been used extensively for wide angle scanning applications. The geodesic analogue of the Luneburg lens is an example of a TEM parallel plate lens which is very difficult to fabricate. The lens is contoured in three dimensions, and for narrow beams at moderate microwave frequencies, presents a serious fabrication problem. This problem is increased because the lens is made up of two such surfaces which must be very nearly identical and which must be accurately nested together to provide the correct path length for all the rays. The metal plate "constrained" lens obviates the fabrication problem by the use of waveguide "constraining" elements at the lens surface. This technique allows the parallel plate transmission line to be planar, but because waveguide is used, the bandwidth for large aperture systems is small. The MUBIS lens overcomes the bandwidth problem by using coaxial cables as the "constraining" elements. Like the metal plate lens, the parallel plate transmission line is planar. This, coupled with the fact that coaxial cables are used, results in a simple wide angle lens which presents few fabrication problems and is broad band. The bandwidth of this lens usually depends on the bandwidth of the array of coaxial probe transitions in the parallel plate region. These probes represent a serious design problem since they must maintain a low VSWR over a wide variation of angles of incidence. In this respect the MUBIS probe array is different from the probe array used

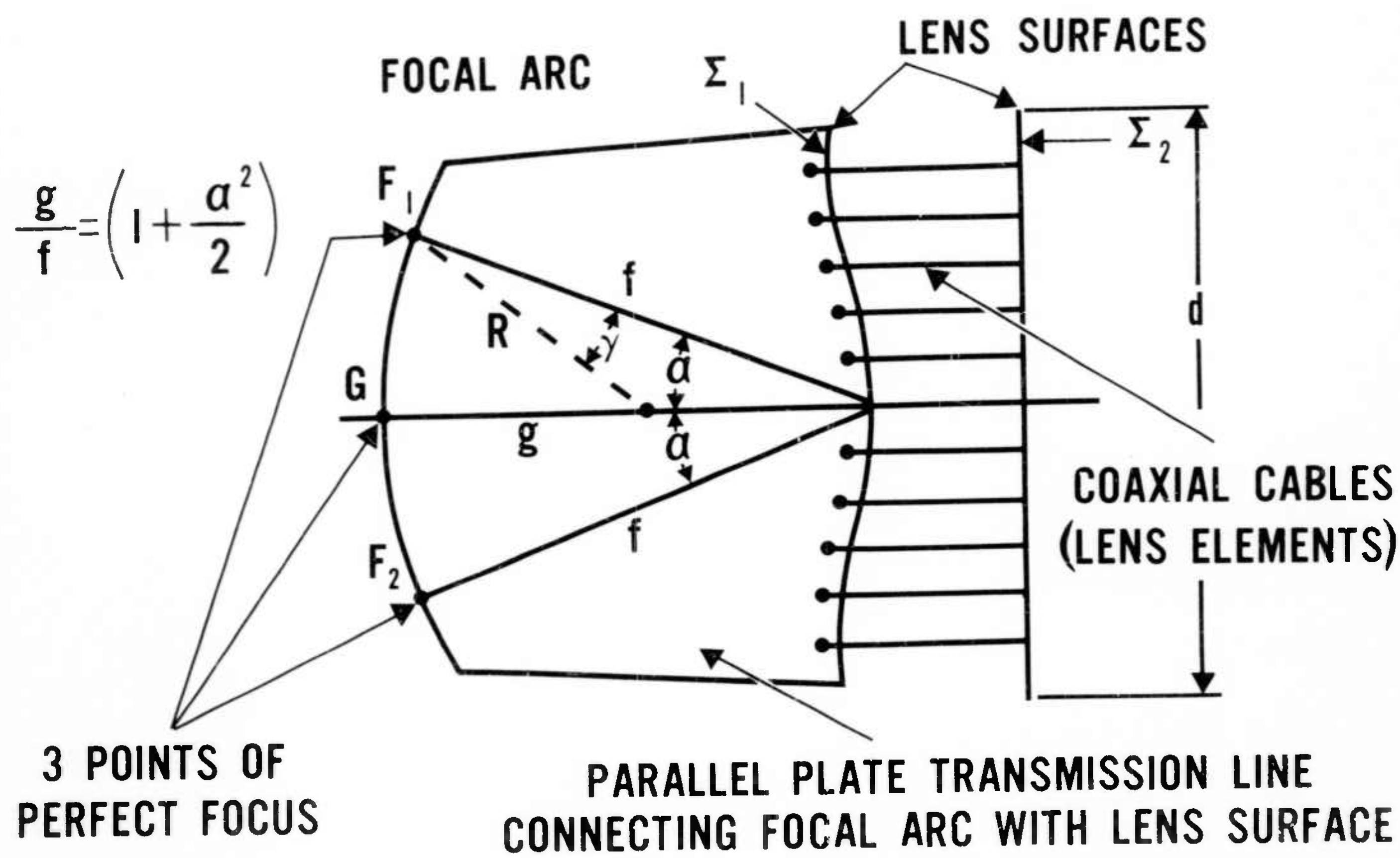

Figure 1-1. Two-dimensional Constrained Lens

on the Geodesic Lens where the radiation in the parallel plate region is always normal to the focal arc, regardless of the scan angle.

Like the metal plate lens, the MUBIS lens does not have a true focal arc. It simply has three points of perfect focus which lie along an arc which is chosen so as to minimize the "off focus" aberrations. Reference 1 indicates that for line sources as long as 100λ and scan angles out to ±35 degrees from broadside, the maximum calculated phase error across the aperture can be made as low as 0.05λ. Since the "off focus" phase errors are small, and consequently the far field multiple beams are very nearly identical, the lens can be used in a monopulse system. Of the two types of monopulse systems, the amplitude comparison monopulse system appears to be the only one which can be used with the lens.

In an amplitude comparison monopulse system, the peaks of the two beams are displaced or "squinted" from the antenna boresight axis. Although the two beams are identical they do not overlap, but rather intersect on the boresight axis at some level. This is easily accomplished on the lens by placing sources of radiation along the focal arc and adjusting the separation between them to obtain the proper crossover level of the far field beam patterns. Scanning of these monopulse beams is accomplished by moving these two sources along the focal arc together as a unit to maintain the proper crossover level throughout the scan. In the Sylvania system this motion is produced by means of a coaxial probe monopulse organ pipe scanner. The design of this system is described in Reference 2.

SECTION 2

SYLVANIA'S EXPERIMENTAL PROGRAM

The experimental program at Sylvania has been principally concerned with the feasibility of combining a coaxial probe monopulse organ pipe scanner with the two-dimensional MUBIS "constrained" lens. The experimental antenna is shown in Figures 2-1 and 2-2. The lens is connected to a line source which feeds a parabolic cylinder reflector to obtain the required directivity in the vertical plane. Azimuthal plane directivity is provided by the line source which is capable of being scanned ±35 degrees through the use of the lens. Scanning is accomplished by moving sources of radiation along the focal arc of the lens. In the Sylvania system, however, this source motion along the focal arc is produced by means of a coaxial probe monopulse organ pipe scanner, as shown schematically in Figure 2-3. As the scanner head rotates, it sequentially energizes groups of probes in the scanner transition region. This energy is transferred by means of coaxial cables to the focal arc of the lens where it radiates into the parallel plate region for eventual collimation by the lens. The design and development of such a system has been described in Reference 2. The experimental results described in this report have shown that such a system is feasible even at relatively narrow half power beamwidths of around 2 degrees. Furthermore, such a system is capable of scanning a monopulse beam out to ±36 degrees from the broadside position with accuracies of about 0. 1 degree. The reason for the relatively poor monopulse accuracy appears to lie in the cable assemblies which comprise the "constraining" elements of the lens which are also used to transfer the energy from the monopulse scanner to the focal arc of the lens. Ideally these cables should have very low VSWR's and also should maintain a constant relative phase difference between cables to obtain obtain optimum system performance. Unfortunately, the particular cable assemblies which were used on the antenna had measured VSWR's as high as 1. 8 to 1. These individual mismatches result in reflections of varying amplitude and phase appearing at the monopulse comparator. This can cause a branch amplitude asymmetry and a channel phase assymmetry both of which affect the monopulse system accuracy.

In addition to the relatively poor match of the cable assemblies, the phase stability between individual cables is another source of error in the system. While the mismatch of the cable assemblies is principally due to the connectors used and therefore not a fundamental problem, the problem of phase stability of the dielectric-filled coaxial cables appears to be one common to phased arrays. Some progress towards the solution is being made by the cable manufacturers such that cables can now be purchased which have relatively good stability over limited temperature ranges. Also, the characteristics of these cables is such that where the absolute phase lengths do change, the relative phase difference between cables can be held to small values. The use of pin or bead-supported air dielectric coaxial lines also appears to offer some help in overcoming the phase stability problem of the cable assemblies.

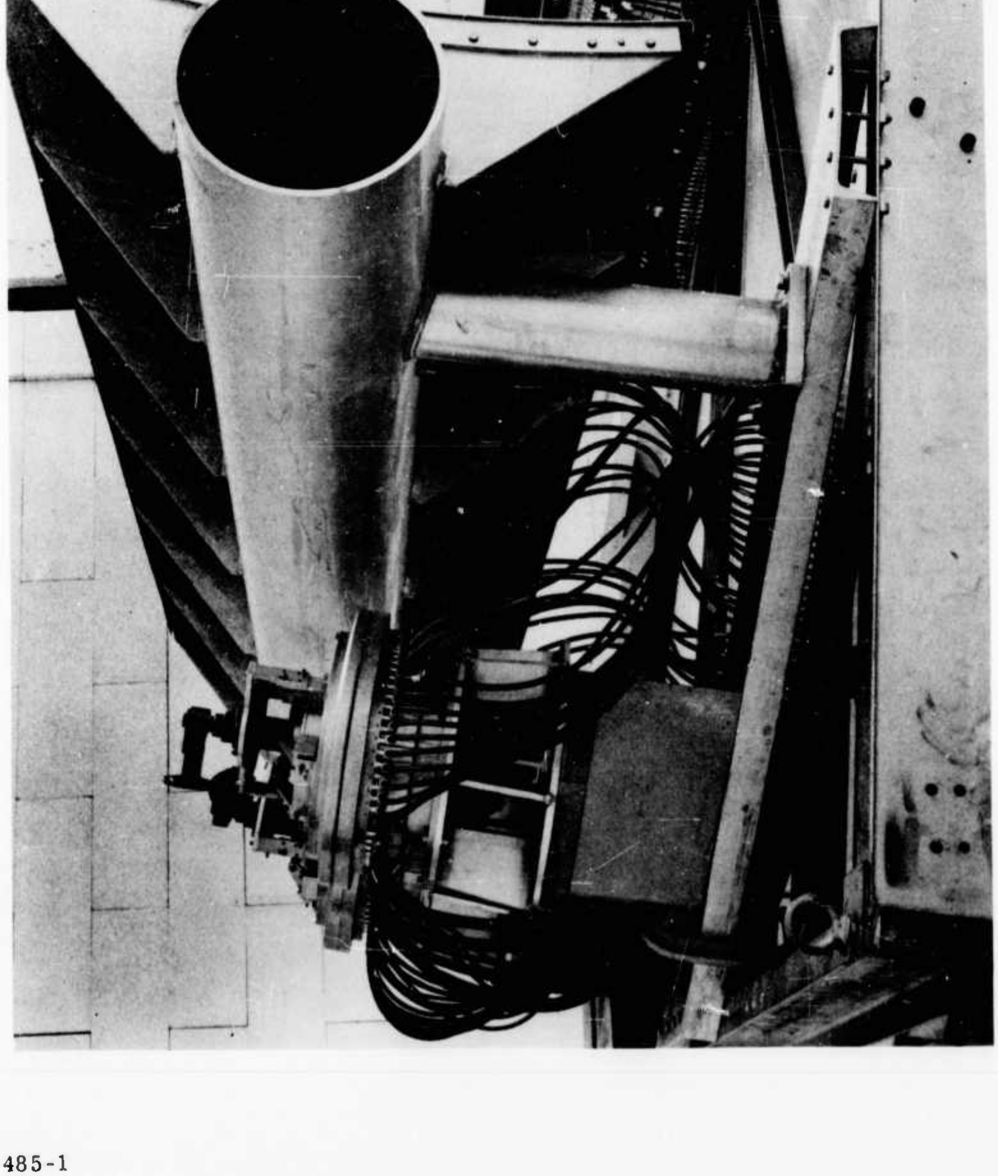

Figure 2-1. Rear View of Completed MUBIS Antenna System

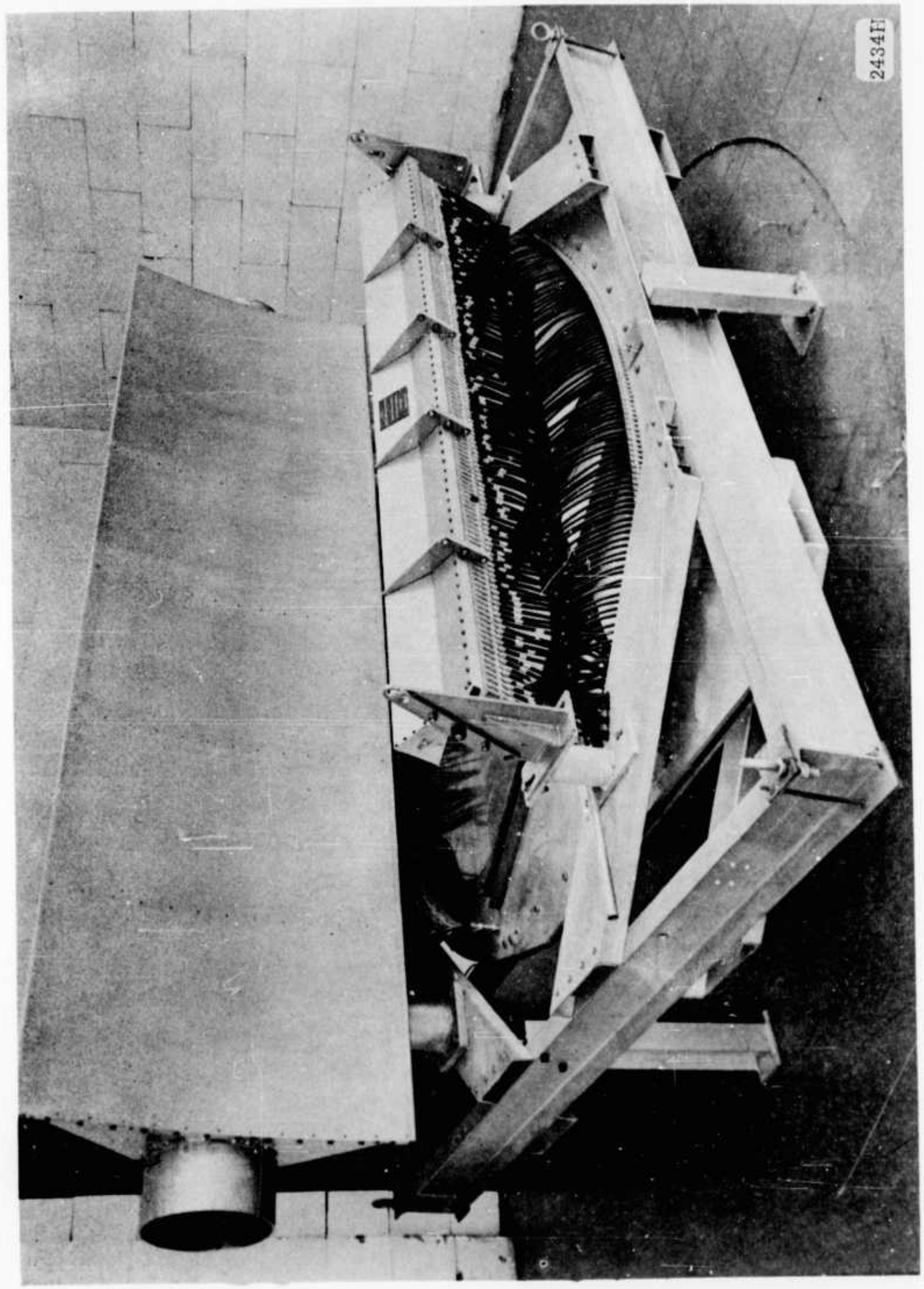

Figure 2-2. Front View of Completed MUBIS Antenna System

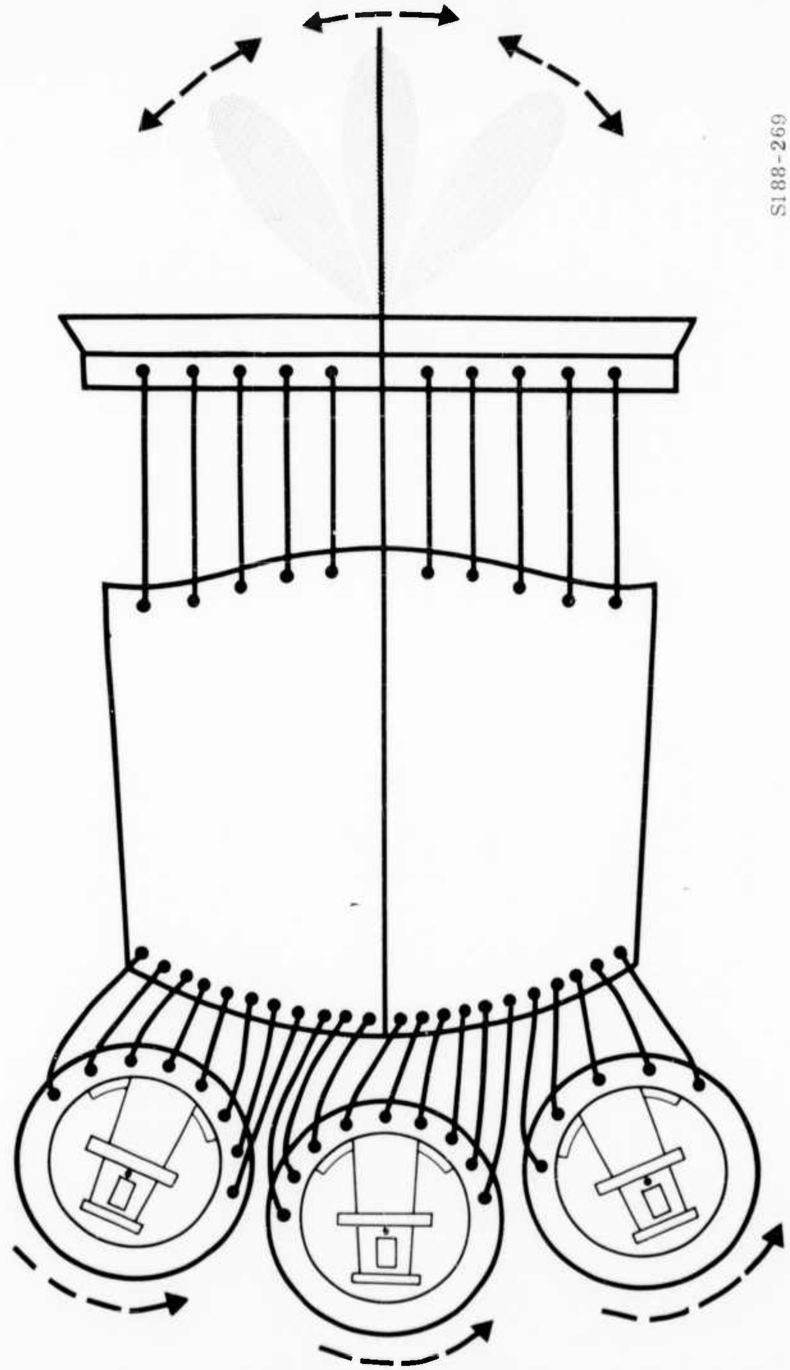

Figure 2-3. Two-dimensional Lens with Coaxial Organ Pipe Scanner

In summary, therefore, it can be stated that although the cable assemblies appear to compromise the monopulse system accuracy, the present state of the art with reference to coaxial cables indicates that this particular problem is not without some possible solution. It should also be noted that the use of coaxial lines as the "constraining" elements of the lens results in an inherently broad band device. The lens itself is computed on the basis of geometric optics and the use of the TEM mode throughout allows for operation over a wider frequency band than if the "constraining" elements were made of dispersive transmission lines such as rectangular or circular waveguides.

SECTION 3

POSSIBLE AREAS OF DEVELOPMENT

The success of the MUBIS experimental program proved the feasibility of combining a coaxial probe monopulse organ pipe scanner with a wide angle two-dimensional constrained lens. Essentially, it showed that the lens could be scanned by sequentially energizing groups of probes along the lens focal arc. The technique of using a focal arc lined with probes which can be selectively excited so as to produce a movable phase center allows for the use of switching techniques to effect a completely inertialess scanning system. While the use of a mechanically driven scanner nearly approaches inertialess scanning, the development of a diode switching matrix would be very desirable and would greatly increase the versatility of the lens technique.

In considering the design of such a scanner, it should be noted that the positioning of the far field beam would be in discrete steps with the incremental change in the angular position of the beam depending on the angular separation between adjacent probes on the focal arc. Due to the design of the lens, this incremental change is proportional to the lens aperture, and since the focal arc probe-to-probe spacing is normally 0.5λ or less, the far field patterns of two adjacent scanner positions will usually provide sufficient overlap. This allows the use of circuitry which would provide interpolation required for detection of targets in the area between adjacent beams. One method of accomplishing this is through the use of a vernier which would vary the position of the apparent phase center between two adjacent scan positions. Although not designed, such a vernier would consist of a power divider and variable attenuator, whose phase remains constant with changes in attenuation. By varying the ratio of power applied to two probe positions along the focal arc, the energy center of gravity can be shifted. This shift is equivalent to a shift in the center of phase. This technique may introduce some aberrations in the far field pattern because a true phase center will not always exist. However, this technique would indeed cause the far field beam to assume a position in space corresponding to some intermediate position of the "pseudo phase" center existing between the two probes. Before such a system could be incorporated into an inertialess scanning system, considerable development effort would be necessary to assess the effects on the far field radiation patterns of the aberrations caused by the absence of a true phase center.

Since the MUBIS lens can be considered as a planar phasing network for a line source, two techniques appear to be able to extend the limits of scan considerably beyond the present ±36 degrees from broadside. Both of these techniques are compatible with the forementioned inertialess scanning technique.

3.1 PHASE SHIFTERS IN COMBINATION WITH ORGAN PIPE SCANNERS

The first of these techniques consists of using phase shifters in combination with the organ pipe scanners. The phase shifters are connected to each of the lens "constraining" elements and are of such values so as to introduce a linear progressive phase shift along the elements of the line source. This phase taper, when added to the taper produced by the lens, tilts the relative position of sector scanned by the lens. By inserting a complete set of two- or three-position ganged phase shifters of the appropriate values in each of the lens elements, the azimuthal scanning capabilities can be increased. Scanning with this technique is a sector scan. The sector to be scanned is determined by the particular phase taper switched in by the phase shifters. Scanning in the sector is accomplished by the organ pipe scanner. If multiple beam capability is desired, a number of organ pipe scanners are used along the focal arc with each scanner independently scanning its own sub-sector.

3.2 VARIATION IN INTER-ELEMENT SPACING

The second technique consists of varying the inter-element spacing on the line source relative to the probe spacing on the lens surface Σ_1. The ratio of these two spacings serves to adjust the angle that the peak of the far field beam makes with the lens axis relative to scan angle, that is, the angle that the radiating source on the focal arc makes with the lens axis. If the probe spacing on the lens surface is maintained fixed, an increase in the line source inter-element spacing decreases the scan angle while a decrease in this spacing increases the scan angle. This technique may present some serious difficulties when one attempts to increase the scan angle appreciably. Foremost are the mechanical and electrical problems associated with the closer inter-element spacings on the line source. Since the maximum probe spacing on the lens should be 0.5λ to prevent the formation of grating lobes in the lens, attempts to decrease the line source inter-element spacing may not be very successful below 0.3λ. However, even with a reduction in the line source inter-element spacing from 0.5λ to 0.3λ while maintaining a probe spacing on the lens surface corresponding to 0.5λ, the scan limit can be increased out to ±70 degrees from the broadside position.

In using this technique, it should be noted that in decreasing the line source inter-element spacing, the total length of the aperture is shortened, while the lens size remains constant. Consequently, if a given aperture is required, the lens size is increased by the same ratio as the element spacing was reduced. This, in effect, is the penalty imposed by the wider angle scanning capability. The converse of this is also true — if there is a requirement for narrow sector scanning, the possibility of decreasing the lens size should be considered.

These techniques for increasing the scanning limits of the MUBIS lens must be approached with the usual caution that is necessary when designing any wide angle scanning system, namely, an examination of the element pattern to determine whether it is broad enough to allow its use to the scan limits without serious deterioration in gain.

SECTION 4

POSSIBLE USES OF MUBIS IN THREE-DIMENSIONAL RADAR SYSTEMS

To determine a target's position, it is necessary to specify three parameters, range, azimuth angle, and elevation angle. Methods for obtaining accurate azimuth and elevation angle information have always been the concern of antenna engineers. Also, the need for narrower beamwidths and higher gain is continually increasing. The MUBIS antenna system, which provides independent multiple beam forming and beam steering functions in one plane from a single stationary antenna, appears to offer a partial solution. Because of its simplicity it can be combined with other techniques capable of scanning in the plane orthogonal to the MUBIS scan plane. The resulting system produces independent scanning in two orthogonal planes. The techniques which are considered in this report may be arbitrarily classified according to the manner in which the MUBIS technique is used. Consequently the following classification was selected:

1) Systems using <u>one</u> MUBIS lens for scanning in one plane combined with the following independent techniques in the orthogonal plane:

   a) Mechanical Scan

   b) Signal Processing Antennas

   c) Inertialess Scanning

2) Systems using <u>two</u> lenses in which the wide angle scanning in one plane is accomplished by applying the MUBIS technique simultaneously to the two lenses. Angular information in the orthogonal plane is obtained by operating on the relative outputs of these two lenses in the following systems:

   a) Amplitude Monopulse

   b) Phase Monopulse

   c) Dual Terminal Arrays

3) Systems using <u>multiple</u> MUBIS lenses in which scanning in one plane is accomplished by applying the MUBIS techniques simultaneously to these lenses. Scanning in the orthogonal plane is accomplished by some other technique.

SECTION 5

SINGLE LENS SYSTEMS

5.1 MECHANICAL SCAN

Since the MUBIS technique offers simplicity and hence reliability in scanning a wide angle planar sector, it is desirable to combine it with a similarly uncomplicated scanning technique in the orthogonal plane. The use of a one-axis, mechanically-rotating antenna mount is an easy and reliable method of accomplishing this. Although this combination is obvious and unsophisticated, it results in a dependable two-axis scanning antenna. The advantages in such a system lie principally in the servo area which is reflected in structural design of the antenna. In any large two-axis antenna, the problem of moving a heavy massive structure is aggravated by the fact that the drive motors for one of the axis (for example, elevation axis) must be incorporated into the moving structure and is carried along with it as the antenna is rotated about the orthogonal axis (for example, azimuth). This weight penalty is further compounded by the need for the additional structural stiffening required to eliminate low frequency mechanical resonances. By restricting the mechanical motion to one axis, this particular problem is eliminated and the prime power requirements are correspondingly reduced.

There are two possible configurations that such a system can assume. In one system elevation scan is provided by the MUBIS technique and azimuthal scan by the conventional rotating mount. By tilting the axis of the parabolic cylinder at an angle of 45 degrees and by using the technique of varying the inter-element spacing of the line source to increase the elevation sector scanned to 90 degrees, complete hemispherical coverage is possible with this system. Multiple beam capability is also possible in the elevation plane, but independent azimuthal control of the separate beams is not possible. This type of antenna may have application in an airport surveillance type of radar.

If a sector scan is desirable, a configuration which gives a rapid azimuthal sector scan by means of the MUBIS technique, with elevation scanning provided by mechanically tilting the reflector and feed, is possible. This type of system may appear unwieldy, but for narrow beamwidths at low frequencies the system has advantages because it eliminates some of the mechanical problems associated with rapid azimuthal sector scanning of a large antenna.

From the foregoing it is apparent that although the combination of a MUBIS lens with a single axis mechanically rotating mount is obvious, it does have practical advantages in providing a simple two-axis scanning antenna system. The advent of interferometric techniques and the use of bistatic radar systems appear to be areas where such an antenna would have definite potential.

5.2 SIGNAL PROCESSING ANTENNAS

Interferometers, Mills Crosses, and Criss Crosses are antennas which belong to a class known as signal processing antennas. They use various nonlinear techniques to enhance a particular antenna characteristic, usually directivity, at the expense of some other antenna characteristics, usually gain and/or resolution. Since these antennas use nonlinear techniques, they are used only as receivers. However, when "a priori" information regarding the target is known, this type of antenna is extremely useful. Therefore, these antennas are suited for radio astronomy and satellite surveillance applications where the path of the target is known prior to its passage over a particular point. The potential use of the MUBIS technique in interferometry and signal processing antennas can best be appraised by first considering how these antennas function.

Most of these systems involve interferometry techniques which are concerned with increasing directionality* in a single plane. In its simplest form an interferometer consists of two identical antennas separated by a distance d, of many wavelengths. The general arrangement of such an antenna is shown in Figure 5-1. For targets sufficiently distant (relative to the antenna separation) so that the two antennas appear to be coincident, the radiation pattern is, by the principle of pattern multiplication, equal to the individual element pattern, multiplied by the array factor of two point sources separated by the distance d. As shown in Figure 5-1, the resulting pattern in the plane of the separation is a multi-lobed pattern with the number of lobes being proportional to the separation distance d, and the envelope of these lobes determined by the antenna element pattern. In the orthogonal plane, the antenna is relatively broad so that the complete radiation pattern is a series of fan beams. At angles near broadside to the array, the spacing between these beams $\Delta\theta$ is proportional to λ/d. Generally, an interferometer is used as a transit type of instrument in which the target travels through the multiple lobes. Knowing the number of lobes and the separation between lobes, information regarding speed and trajectory can be computed.

The radiation patterns of each of the interferometer elements are the same and are usually moderately directive. This is necessary to localize the sector covered by this series of fan beams as well as to provide gain. Additionally, in the interest of versatility, the two elements of the interferometer are capable of scanning in two planes. In general, these elements consist of two large steerable parabolic dishes deployed along an E. W. or N. S. base line. A number of schemes exist for processing the data received. These are generally nonlinear in nature. The relative merits of these systems are beyond the scope of this report. However, it should be noted that these are compatible with the MUBIS lens technique.

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*Directionality is defined as the ability to locate a single point target and is equivalent to directivity only in the sense that it exhibits similar pattern characteristics for a single point target.

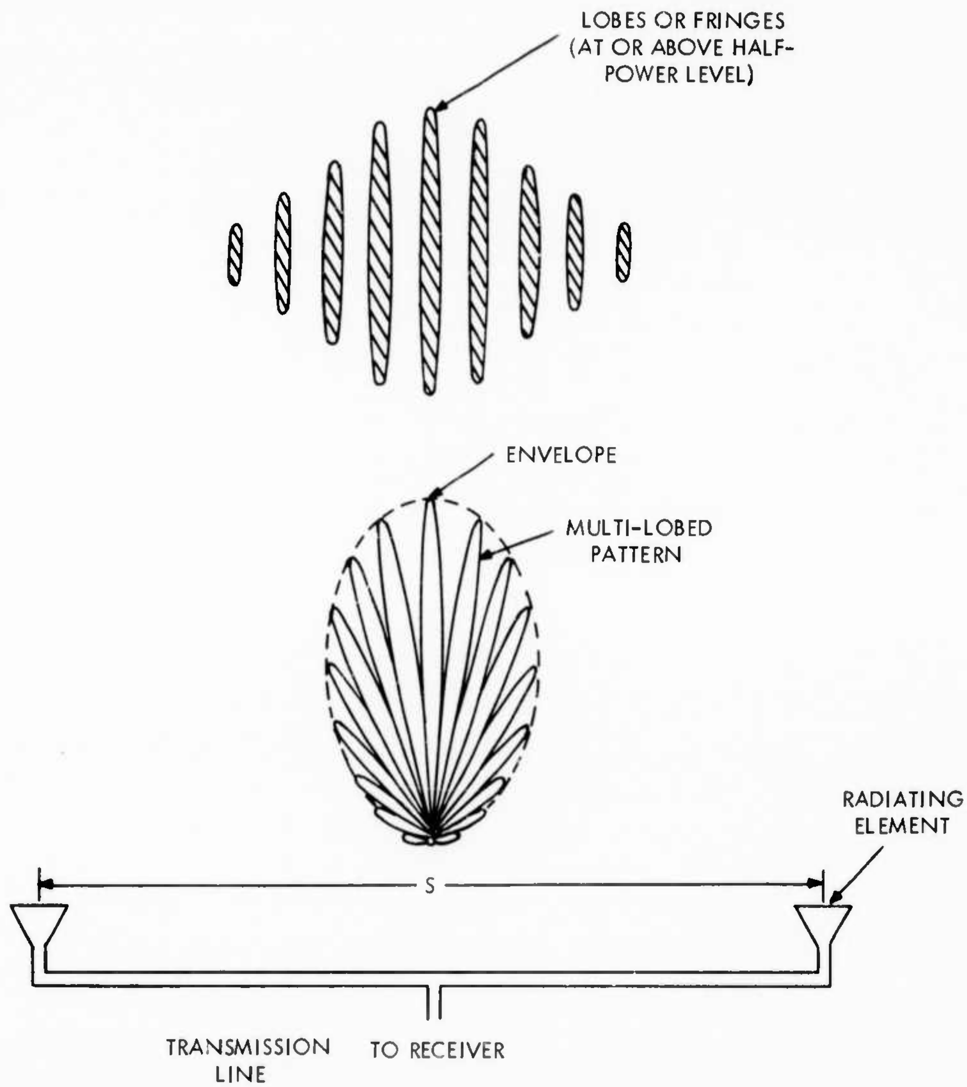


Figure 5-1. Two-element Interferometer with Patterns

Variations of the basic interferometer are the Multi-Element Interferometer, the Mills Cross, and the Criss Cross antennas. The Multi-Element interferometer is based on the same principle as the two-element interferometer, but has more elements which are spaced closer together. They are still considerably further than $\lambda/2$ apart, however. This takes advantage of the fact that as the number of elements in an array is increased (with the separation held constant), some of the sidelobes are suppressed and there is a greater distance between mainlobes. See Figure 5-2. The envelope of the pattern can be steered by steering the individual antenna elements in unison or by adjusting the phase between elements to produce a linear progressive phase taper.

The Mills Cross consists of two long linear arrays of $\lambda/2$ spaced dipoles arrayed in the form of a cross. These two arrays form a pair of orthogonal fan beams in space. The array outputs are connected to respond only to sources within the area common to the beams of both arrays. The antenna pattern on reception is therefore effectively a pencil beam whose size equals the area common to both fan beams. Motion of this pencil beam is accomplished by adjusting the phase taper in each of the arrays to tilt the two orthogonal fan beams in their respective planes. The resulting intersection of these fans determines the position of the effective pencil beams in space.

The Criss Cross array or crossed multi-element interferometer combines the principles of the multi-element interferometer and the Mills Cross. It consists of two multi-element interferometers at right angles to each other. Since the interelement spacing of the multi-element interferometers is considerably greater than $\lambda/2$, the effect of placing them at right angles is to produce a series of intersecting fan beams with the two mutually perpendicular sets of lobes forming a grid. By the use of techniques similar to those of the Mills Cross array, the system produces a number of pencil beams at the points of intersection of these fans. Steering of this cluster of pencil beams is accomplished by steering the elements in each arm either by means of phase shifters or by mechanically steering each element.

The principal area in which the MUBIS concept could be used is in providing a simple reliable interferometer element when used in a manner similar to the antennas shown in Figures 5-3 and 5-4. The advantage of these configurations over the two-axis mechanically steered paraboloidal reflector have been stated on Mechanical Scan. These advantages would reflect substantial savings especially when applied to the large number of elements which might be used in a multi-element interferometer.

Since the Mills Cross consists of two line sources, it appears that the MUBIS lens might have a possible application as the power divider and phasing network necessary to feed each of these line sources. The simplicity of the lens makes it ideal for such an application. It can be made to provide some degree of amplitude taper as well as the phase taper necessary for moving the fan beam. At low frequencies, in the region of four meters, such a lens system might present some difficulties since the metal plates for the

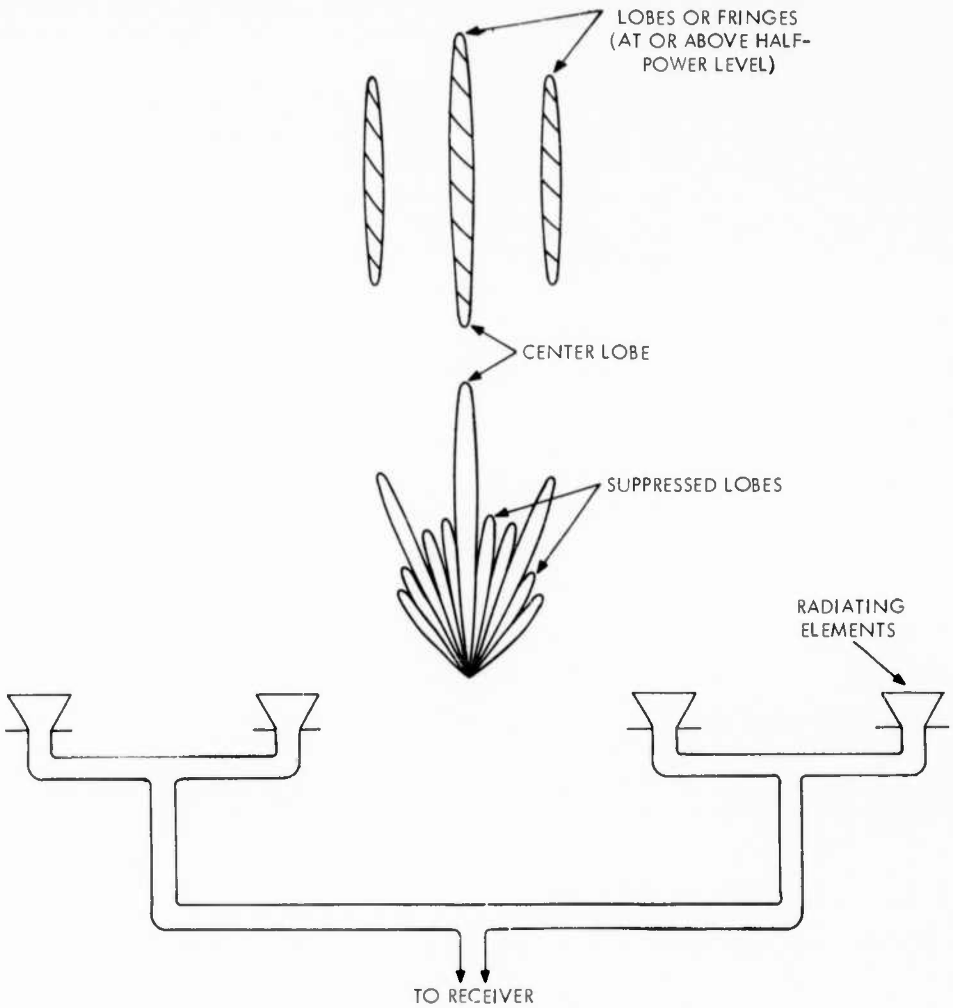


Figure 5-2. Multi-element Interferometer

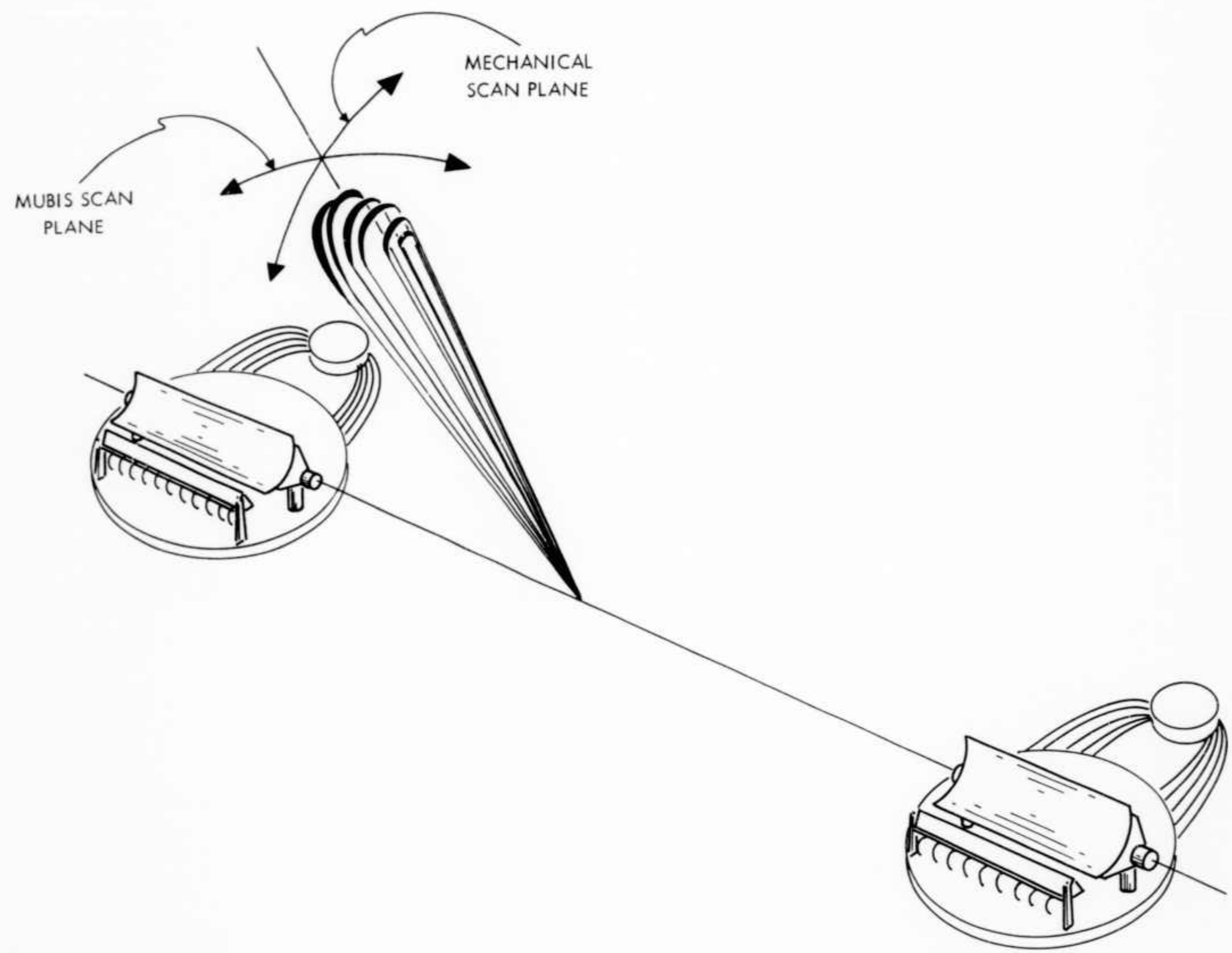


Figure 5-3. Possible Two-element Interferometer with MUBIS Scan Plan Horizontal

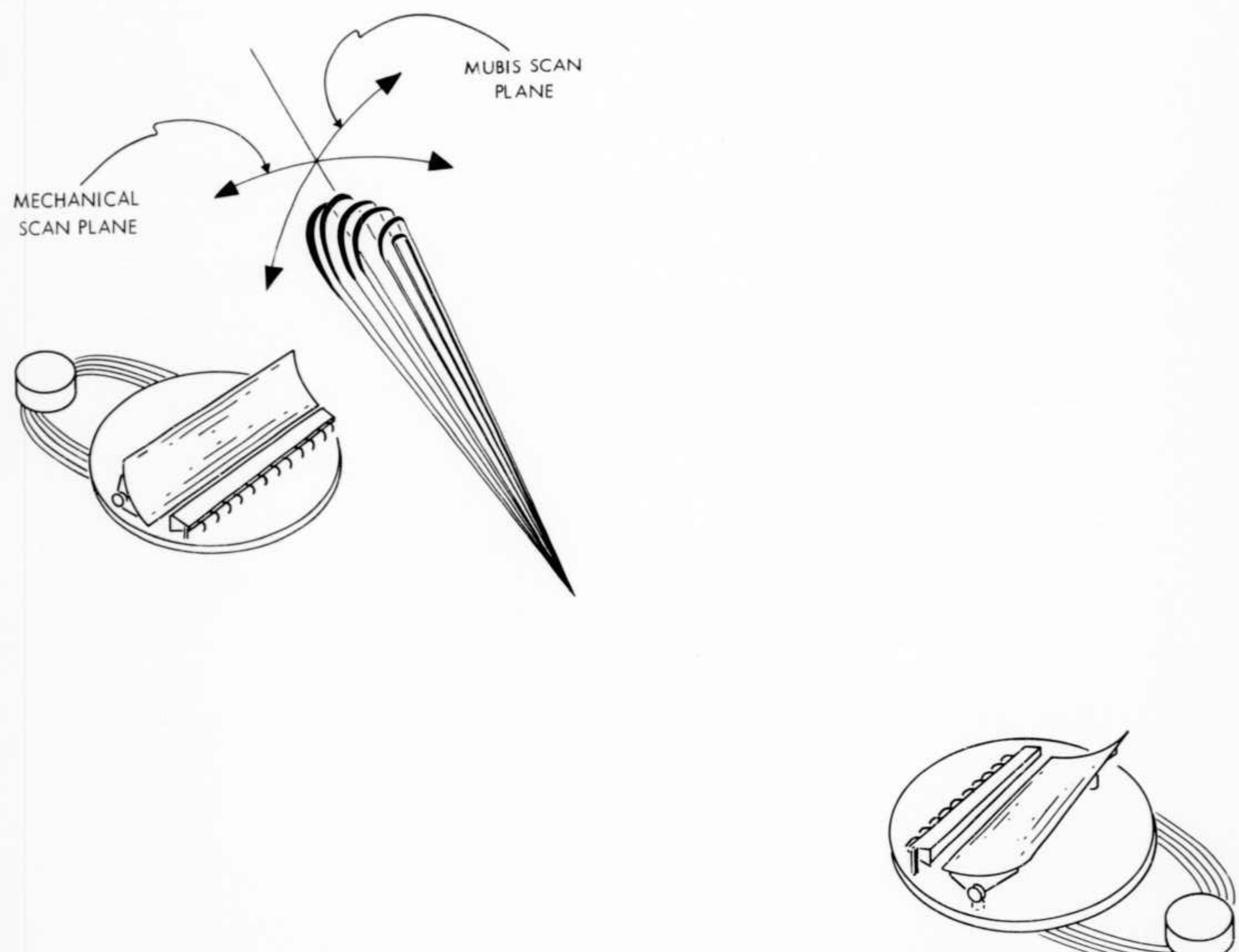


Figure 5-4. Possible Two-element Interferometer with MUBIS Scan Plane Vertical

lens would occupy about forty acres, assuming a 100λ long line source. However, at the higher frequencies such a system might prove feasible. Furthermore, if the applications are such that the Mills Cross would be required to scan a ±20 degree cone about the zenith or about some particular ascension angle, a reduction of about fifty percent in the size of the lens could be accomplished by adjusting the ratio of lens probe spacing to line source inter-element spacing as described in Section 3. 2 of this report.

5. 3 INERTIALESS SCANNING

The simplicity of the MUBIS lens and the low inertia of the coaxial probe organ pipe scanners make it very desirable for possible combination with existing inertialess scanning techniques in the orthogonal plane. Furthermore, since completely inertialess scanning is feasible through the use of a diode switching matrix with the MUBIS lens, a completely inertialess two-dimensional scanning system is possible. There exist three general types of inertialess scanning techniques which can be combined with single MUBIS lens to provide independent control of the elevation aperture phase taper. These consist of:

1) Frequency Scan
2) Phase Shifting
3) Beam Switching

SECTION 6

FREQUENCY SCANNING POSSIBILITIES OF MUBIS

Of the inertialess scanning techniques available for possible combination with MUBIS, frequency scan is the simplest from an antenna standpoint. The MUBIS lens is ideally suited for such a combination because it is computed on the basis of geometric optics and uses the TEM mode throughout. In a typical MUBIS – frequency scan system, wide angle scanning in the azimuth plane is accomplished by one or more coaxial probe organ pipe scanners working in conjunction with the lens. Scanning in the elevation plane is by means of a frequency scanning technique. Figure 6-1 shows a system configuration capable of performing this two-axis scanning. The coaxial cables which comprise the lens elements are each connected to a vertical line source. These line sources are identical and arrayed side by side in the horizontal plane, with the spacing between each of them determined by the particular lens design. This results in a two-dimensional array of radiating elements whose elevation phase taper is adjusted and independently controlled by means of frequency and whose azimuthal phase taper is controlled by the lens.

The greatest potential of the system is in a multiple beam application. In such a system two or more scanners are arrayed along the focal arc so that each scans its own azimuthal sector. The vertical line sources can be designed so that they have a number of "scan bands" in the operating bandwidth of the system. By operating each of the scanners in a different scan band, a number of independent multiple beams are generated in which both the azimuth and elevation scanning functions of each scanner can be separately controlled. This combination of frequency scan and MUBIS results in a versatile system with a minimum of antenna components. It does, however, suffer from the objections raised against a frequency-scanned system: 1) the greater susceptibility to ECM since the surveillance of a particular point in space is limited to a particular frequency or at best a number of discrete frequencies, depending on the number of scan bands available, 2) the need for complex receivers and transmitters, which can operate over a broad frequency band and which have provisions for accurate frequency control and read-out.

In evaluating the vertical line sources for use with the MUBIS lens, consideration should be given to the constraints imposed on their design by the lens. The principal difficulty is in the inter-element spacing between adjacent line sources. In general, the line source for a frequency scan system consists of a series-fed, travelling-wave array. One of the more common methods of constructing such an array is a waveguide structure using loosely coupled slots as the radiating elements to provide the phase delay. If the slots are in the broad wall of a TE_{10} dominant mode waveguide, the minimum spacing between the adjacent arrays is the width of the waveguide. Since this dimension is $\lambda/2$ at the cut-off frequency, it will be greater than $\lambda/2$ at the operating frequency. This fixes the range of the minimum possible horizontal spacing at 0.55λ to 1.0λ. At extreme angles

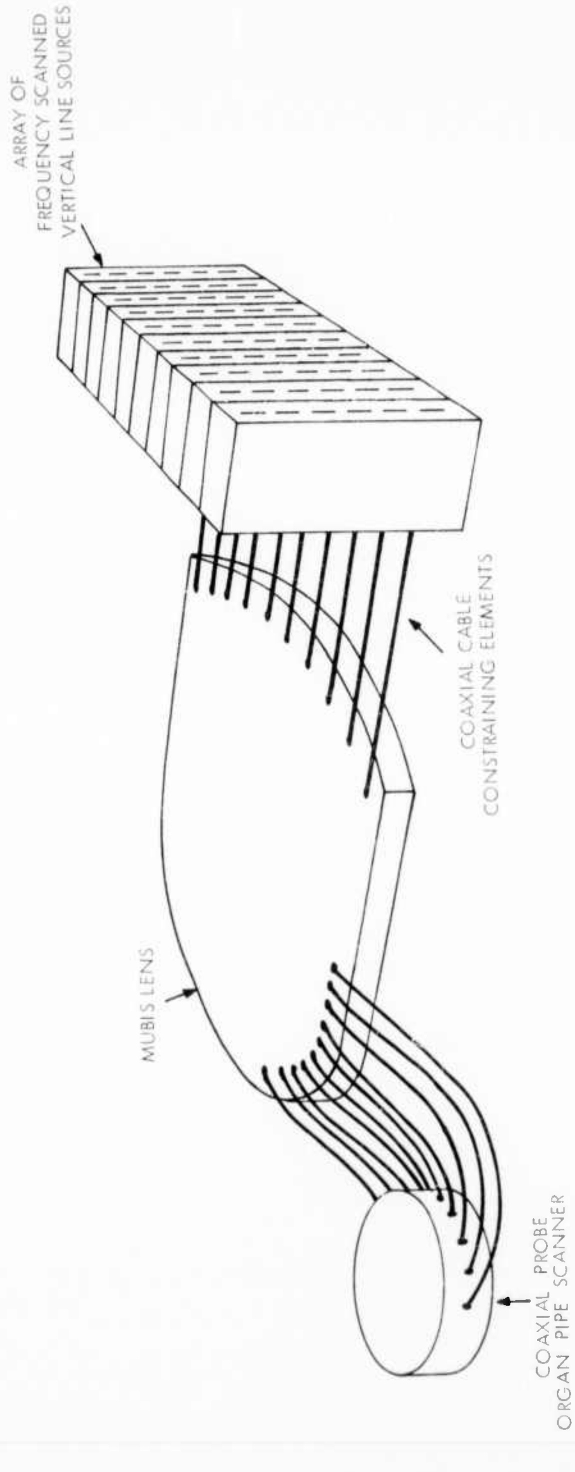


Figure 6-1. System Configuration for Implementing Frequency Scanning Technique

of scan in the horizontal plane this is apt to give rise to grating lobes. Furthermore, to take advantage of the technique described in Section 3.2 which increases the MUBIS scan angle by decreasing the inter-element spacing, it is desirable to have a spacing less than 0.5λ. The use of edge-fed slots in a waveguide also does not appear promising since, to achieve resonant length, it becomes necessary to cut the slot partly into the two broad faces of the waveguide. This precludes the possibility of butting the waveguides together or even spacing them closely since the proximity of the adjacent guides would adversely affect the slot resonance and the element radiation pattern. The desirability of having a number of scan bands over which the system will operate further aggravates this mechanical problem since it requires that the waveguide be folded in a serpentine manner to increase the number of wavelengths between adjacent radiators. Summarily, therefore, it can be stated that elevation scanning techniques which employ waveguide elements arrayed in the horizontal plane should not be used with MUBIS if the wide angle scanning capabilities of the lens are to be utilized to their maximum potential.

Possible solutions to the problem of mechanical interference of the line sources might be techniques to reduce the waveguide dimensions by using ridge waveguide or by loading the waveguide with dielectric. Both of these techniques might work on longitudinal slots in the broad wall of the guide, but would not be effective in the case of edge-fed slots since these slots would still have to extend into the broad wall to maintain their resonant length and therefore would not allow the closer spacing of the vertical arrays. The serpentine feed would also continue to be a problem in the case of the edge-fed slots.

The use of stripline techniques does offer hope of solving some of the mechanical problems associated with the requirement of close inter-element spacing (see Figure 6-2). Series-fed or parellel-fed arrays, having long serpentine lines to allow for a number of scan bands can be closely spaced without too much difficulty. In the design of these arrays, obviously, the mechanical interference of the radiating elements should also be considered. However, this should not be a serious problem since there exist elements for both vertical and horizontal polarization which have a narrow dimension for use in closely spaced arrays.

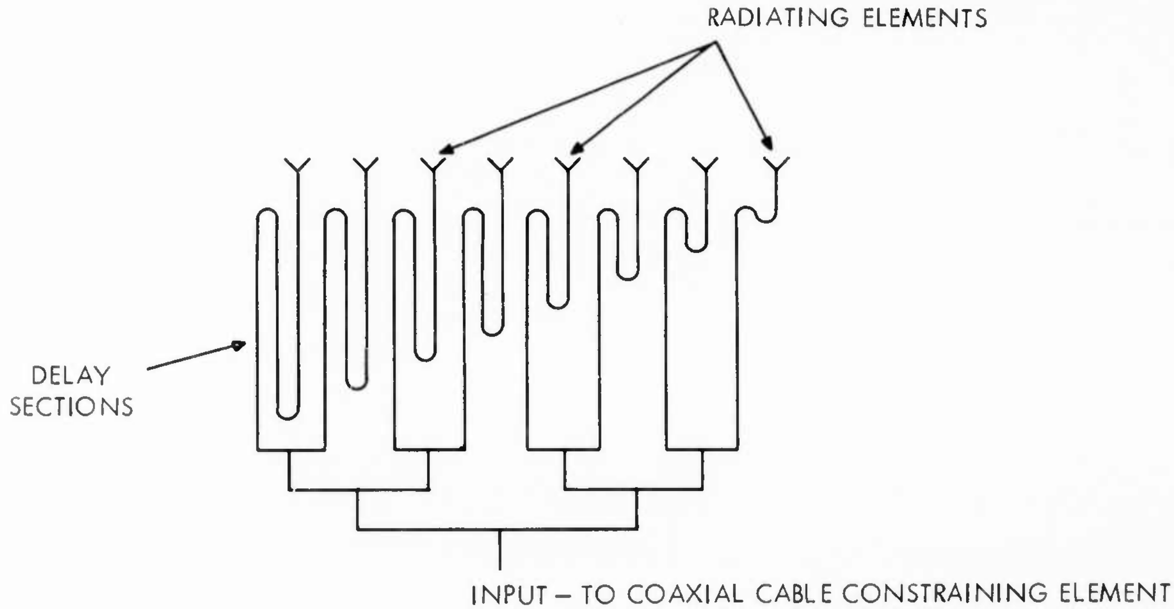


Figure 6-2. Parallel Fed Frequency Scanned Array Module in Stripline

SECTION 7

BEAM SWITCHING CONCEPT

Another approach to the problem of inertialess scanning in the elevation plane is the beam switching concept. In this type of system a planar multiple beam forming matrix is employed, which provides a number of inputs, each of which corresponds to a different position in space. Scanning in one plane is produced by switching the transmitter and/or receiver to the desired inputs. Therefore, in addition to a multiple beam forming matrix, a switching network is also required. For inertialess scanning this switching network uses diode switches. In combining this technique with MUBIS, each of the cables which make up the lens constraining elements are connected to an elevation scanning module. These modules are all identical and consist of the beam forming matrix and the beam switching network. Figure 7-1 shows a possible method of implementing such a system. Azimuthal scanning is accomplished by means of the scanners operating through the lens while elevation scanning is controlled by simultaneously applying the appropriate bias signals to the diode switches in each of the elevation modules.

A typical elevation module, represented in Figure 7-2, consists of a beam forming matrix and a corporate feed structure of double-throw diode switches which comprises the switching network. In general, if the number of beams required to fill an angular sector is 2^n, then n is the number of diode switches through which the signal must pass to reach any given beam input. The total switching loss in this type of arrangement is therefore $n\alpha$. The current state of the art indicates that attenuations α as low as 0.2 db are possible at L-Band. An alternate switching arrangement is also shown in Figure 7-2. This requires that the signal pass through only one switch. However, it has been found that the many "open" channels connected to the one "on" channel increases the losses so that it is doubtful whether this arrangement really offers any advantage as far as loss is concerned. There is also a limit to the number of outputs which can be provided with this technique due to mechanical and electrical interference problems as more lines are brought into a common point. Either arrangement requires that the diode handle the full power appearing at the input terminal at the network.

7.1 THE BUTLER SYSTEM

Two common beam forming matrices which can be used for this technique are the Butler and the Maxson systems.

The Butler System consists of symmetrical hybrids with fixed phase shifters and provides one beam for each antenna element. A four-element system illustrating the principle of operation is shown in Figure 7-3. The hybrid used is the type that has 90-degree phase difference between its two output arms. Each of the four beams formed

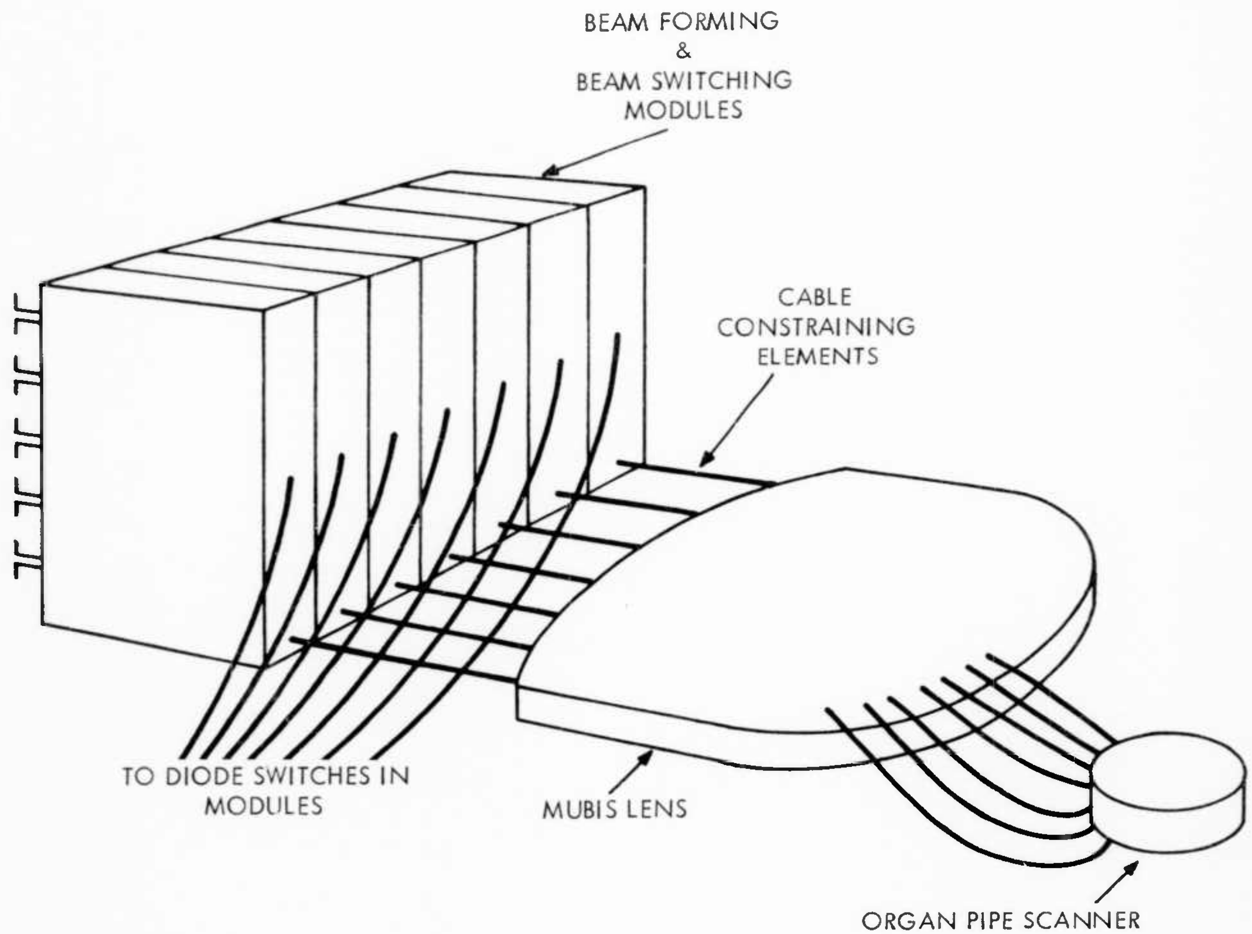


Figure 7-1. Possible Method of Combining a MUBIS Lens with a Beam Switching Technique

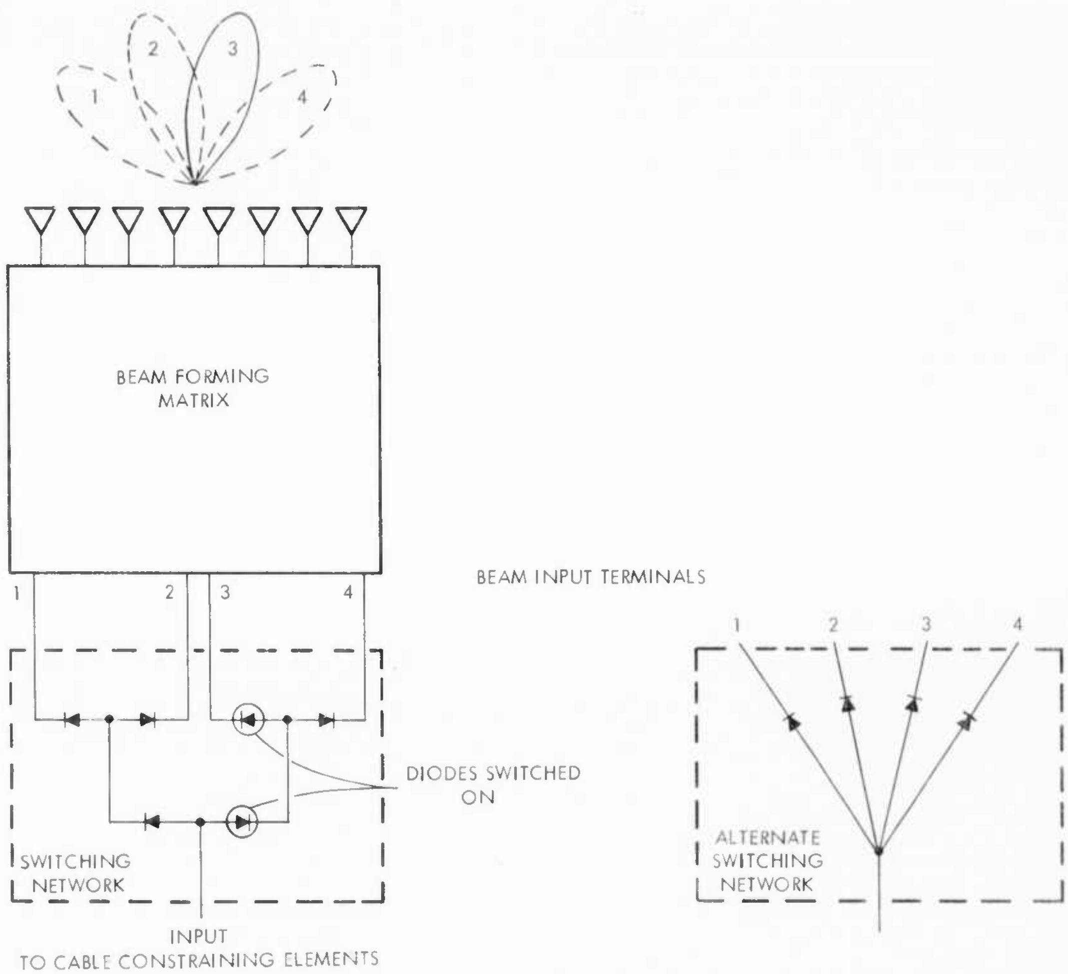
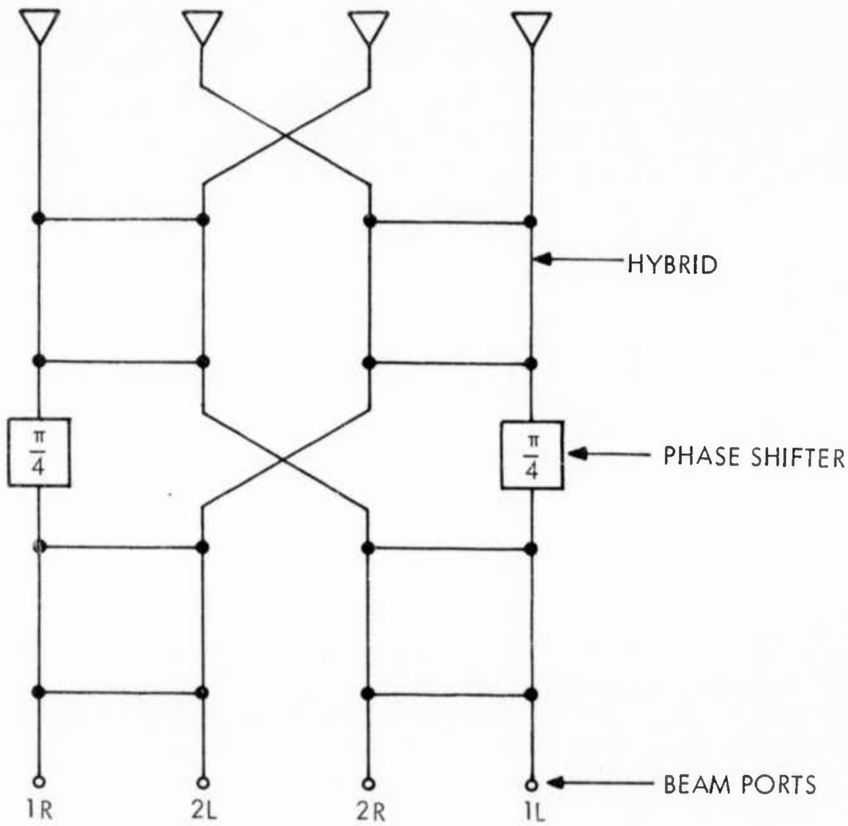


Figure 7-2. Beam Switching Module



NOTES: 1R IS THE FIRST BEAM TO RIGHT OF BROADSIDE. HYBRIDS HAVE $\pi/2$ RADIANS PHASE DIFFERENCE BETWEEN OUTPUT PORTS

Figure 7-3. Four-element Butler System Module

uses all of the hybrids nearest the antenna elements and since the same hybrid is shared by many beams, there is a significant reduction in the number of hybrids used relative to other hybrid systems. However, the radiation pattern characteristics of the Butler multiple beam forming system have some constraints due to the orthogonality of the beams. An examination of the feed system indicates that if energy is incident from a direction corresponding to the peak of one beam, no energy is coupled to any other beam line output. Thus the peak of the beam produced by one port can only be directed in a direction where nulls exist in the beams produced by other ports. This property of mutual orthogonality in the beams also implies that the positions of the beams in space will vary with frequency. This fact is to be expected, since the 90-degree phase shifts in the hybrids generally do not appreciably change over small bandwidth, but the distance between radiators in terms of wavelength does change with frequency. As the frequency is varied a constant phase difference is applied across a varying aperture.

7.2 THE MAXSON SYSTEM

The Maxson System is a multiple beam forming system capable of producing a number of beams in desired directions. A two-beam, four-element system is shown in Figure 7-4. Each connection of lines represents a directional coupler, and the phase shift of each length of line is represented by the physical line length. By exciting the proper input terminal, the correct amplitude and phase are produced for a given beam. For operation with the MUBIS lens the technique is similar to that of the Butler System. The Maxson System requires considerably more design effort than the Butler System since each coupler has a different value of coupling. Furthermore, the Maxson System requires more components than the Butler System. The apparent advantage of a Maxson System is the ability to adjust the amplitude taper across the aperture. And, the number of beams possible with a Maxson System is not dependent on the number of elements in the aperture. The desirability of using one type of beam forming matrix over another is not considered in this report, but to describe the systems and to indicate the manner in which they can be combined with MUBIS are within its scope.

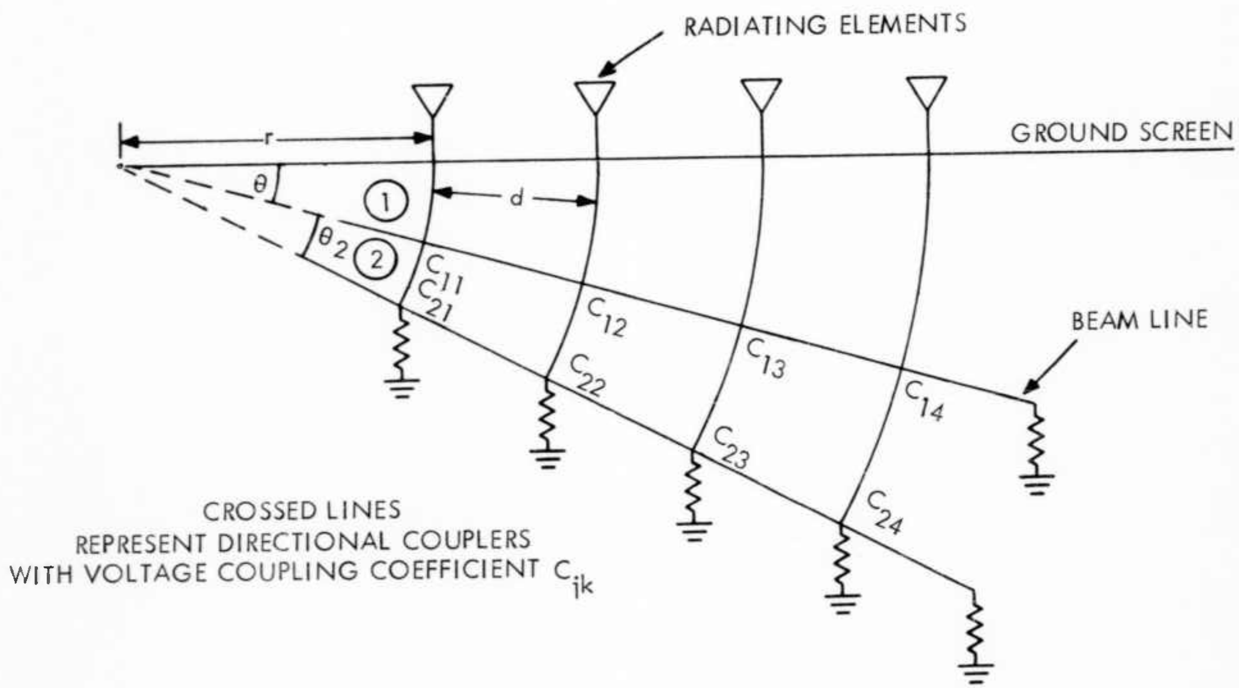


Figure 7-4. A Two-beam Maxson System Module

SECTION 8

PHASE SWITCHING CONCEPT

Phase switching is another technique which can be combined with MUBIS to provide scanning in the orthogonal plane. In operation, this technique is similar to the beam switching technique. The lens cables are each connected to identical phase switching modules and elevation scan is produced by switching all the modules in unison. Of course, azimuth scan is accomplished by the lens action. A typical phase switching module is shown in Figure 8-1. The signal from each of the cables is split up by a power divider and fed through a set of electronically switched phase shifters to the elements of the array. The signal for each element is made to travel a particular path and hence delayed a given amount by means of the diode switches. Since these differential phase shifts are produced with TEM line (strip line or slab line), they are really differential line delays and hence the beams remain fixed in space because they are independent of frequency.

Phase switching has an advantage over beam switching in that the power handling requirement for the diode switches is reduced in proportion to the number of elements in the array. Conversely, a disadvantage to the phase-switching system is that the switching losses are higher.

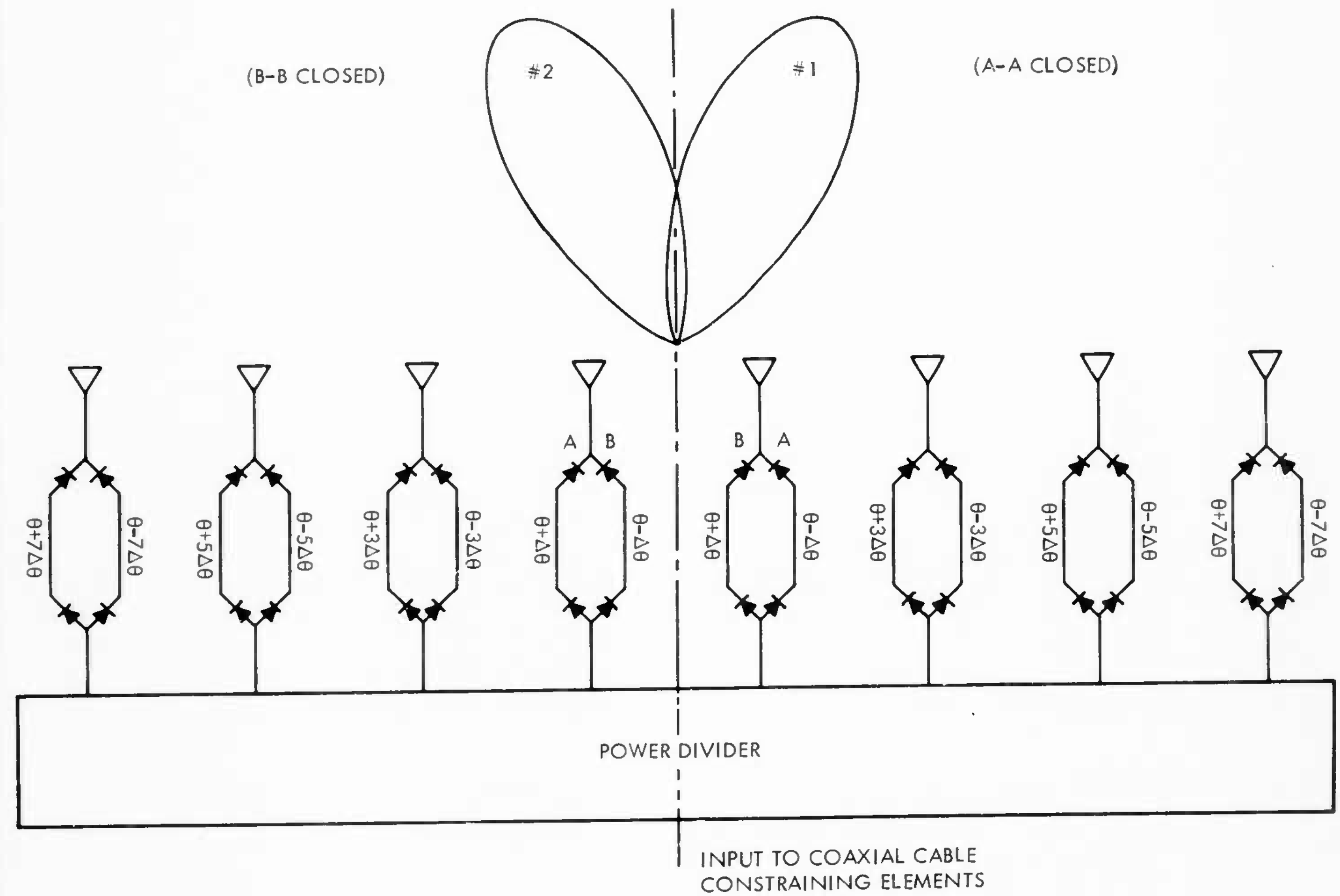


Figure 8-1. Phase Switching Module

SECTION 9

DUAL LENS SYSTEMS

As previously indicated, there is an increasing demand for high data rate antennas for both detection and tracking of high speed targets. One of the factors which must be considered when specifying such antennas is the dependence of the azimuth sweep rate on the elevation scan data rate. This data rate is limited by the need for a sufficient number of hits per scan to provide reliable target detection. Conventional two-axis systems are sometimes too slow because the azimuth scan must be slow enough to allow a sufficient number of pulses to be transmitted in each elevation sector covered by the by the beam. The multiple beam aspect of the MUBIS technique alleviates this problem by dividing up the azimuthal sector being scanned into a number of smaller sub-sectors each with its own scanner. This allows a longer dwell time in each element of space scanned by a beam. Further savings in scan time can be effected by increasing the elevation beam-width, but this is done at a sacrifice in elevation accuracy. However, if this beam broadening is effected in an elevation monopulse system, the accuracy with which the angular position of a target can be determined is improved by at least a factor of ten over the conventional Rayleigh criterion for resolution, which is equal to the half power beamwidth of the radiation pattern.

The transmitting function for a monopulse system is the same as for a conventional radar, (that is a pulse of RF energy is radiated, illuminating the area included within the antenna beamwidth). On receive, however, the signal is utilized by two channels, a sum and a difference channel. The sum channel is similar to the operation of a conventional radar, where a maximum signal level is obtained for radar return signals arriving along the boresight axis of the antenna, and the degree of target resolution is determined by the antenna beamwidth. In the difference channel, however, an opposite condition exists where a minimum signal is obtained for signals arriving along the boresight axis of the antenna. The antenna characteristics and RF circuitry are such that this minimum signal in the difference channel defines the lowest point of a deep sharp null, which permits the mono-pulse system to measure target angles much more accurately than conventional radar systems having the same antenna beamwidth.

Two elevation monopulse configurations are possible with the MUBIS lens technique, Amplitude Sensing Monopulse and Phase Sensing Monopulse. These two systems differ only in the antenna configuration, not in operation. In addition to the conventional monopulse systems, there exists a class of antennas referred to as dual terminal antennas which operate in a manner similar to a phase sensing monopulse system.

It should be noted that the dual terminal antennas and both types of monopulse systems provide reasonable accuracies within a narrow elevation sector about 10 degrees

to 15 degrees. It is doubtful that these techniques could be extended so that a 90-degree sector could be covered with the same accuracy since the absolute error is proportional to the beamwidths involved. These antennas do, however, have application in non-inertialess systems where a mechanical elevation drive can adjust the sector over which the aforementioned inertialess systems are to be used.

9.1 AMPLITUDE SENSING MONOPULSE SYSTEM

An amplitude sensing monopulse antenna system is constructed using a single aperture antenna having two or more closely spaced feeds producing a radiation pattern which is displaced from the antenna boresight axis. This displacement angle is a function of the separation of the feed horn phase centers from the focal point of the antenna aperture. Although the antenna patterns are identical, they do not overlap as in the phase sensing system. The displaced patterns do intersect on the boresight axis of the antenna. Therefore, for all signals within the beamwidth of the antenna, except those arriving along the boresight axis, unequal signal amplitudes will be induced in the feed. When the two signals are subtracted a null will be produced for only those return signals arriving along the boresight axis where the feed horns have equal signal voltages.

A possible method of implementing this system with the MUBIS technique is shown in Figure 9-1. Two-line source feed horns are symmetrically displaced about the axis of a parabolic cylinder such that two squinted elevation beams are produced. The coaxial probe monopulse organ pipe scanners which provide amplitude monopulse beams in the azimuthal plane for each lens are ganged so that their beams scan in unison. Elevation information is obtained by combining the outputs of these two scanners with RF monopulse circuitry which is used in a conventional four-horn, azimuth-elevation monopulse system.

Of the problems to be expected in the design of such a system, the proper placement of the two displaced feeds appears to be a formidable one. Since this is an amplitude sensing monopulse system in elevation, the two-line source feeds are displaced either side of the focal line of the parabolic cylinder. The feeds and associated cables generally produce a substantial aperture block unless an offset feed system is used with half parabolic cylinder reflector.

However, the use of a half parabolic cylinder precludes the possibility of symmetrically offsetting the feeds. The aperture distribution across the reflector is therefore different for each line source feed, and the resulting far field patterns from each feed are not identical. This tends to cause an error or boresight shift because it introduces an amplitude asymmetry into the monopulse system. This error would be of consequence in the highly accurate system, but the resultant accuracy would still be greater than an equivalent system not having a monopulse capability.

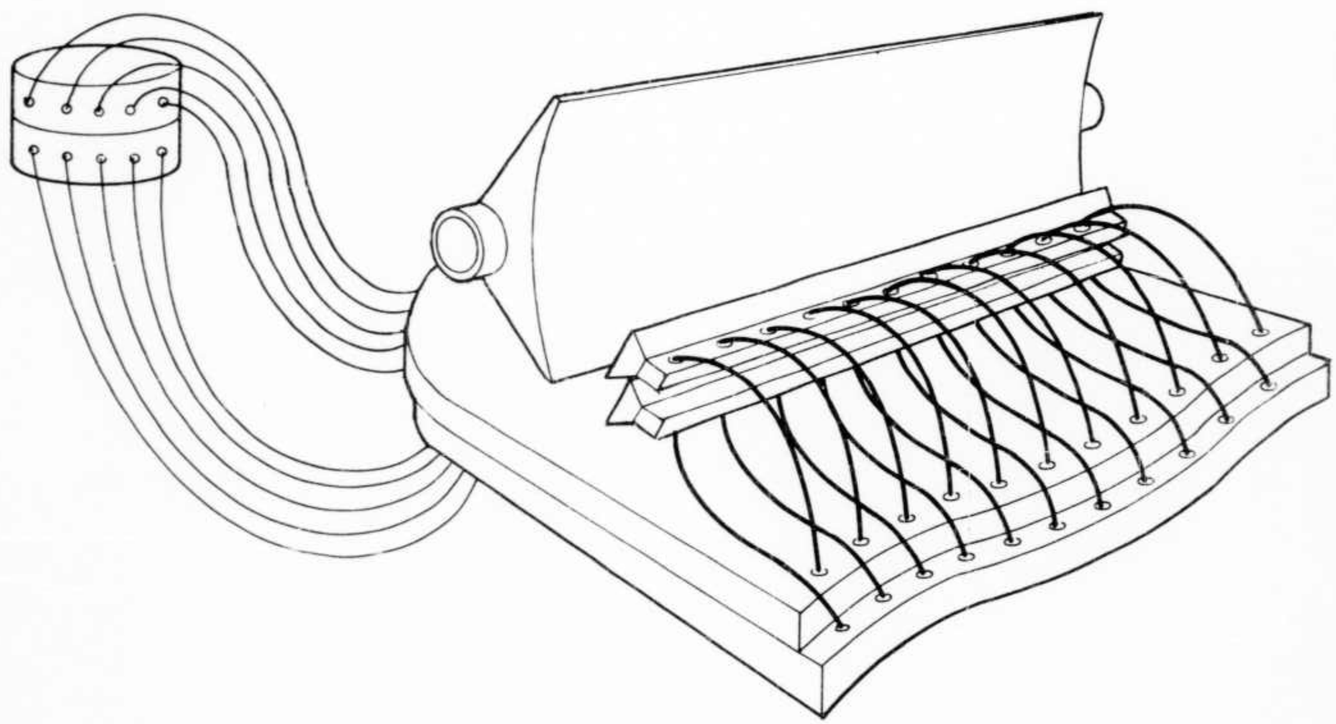


Figure 9-1. Possible Antenno Configuration for Amplitude Sensing Elevation Monopulse System

9.2 PHASE SENSING MONOPULSE SYSTEM

A phase sensing monopulse system is constructed using two or more antenna apertures separated by several wavelengths. The antenna apertures, each having a single feed, produce identical radiation patterns which are symmetrical about their individual boresight axes. Since the individual axes are parallel, their far-field radiation patterns are almost overlapping. In the receive condition this gives essentially an equal amplitude signal in each antenna for targets which occur in their beamwidths. For targets on boresight these equal amplitude signals are in phase. However, for targets off the boresight axis there is a time or phase delay between them due to the spacing between the antennas. Thus, due to the phase characteristic of the received signals, the addition and subtraction of these separated feed signals in the monopulse comparator results in establishing a well-defined antenna boresight axis which is midway between and parallel to the individual antenna aperture boresight axes.

Figure 9-2 shows a possible method of implementing an elevation phase-sensing monopulse system while using the MUBIS technique in the azimuth plane. Two separated, half-parabolic cylinder reflectors are fed by their respective line sources. The effective phase centers of each aperture are separated by a number of wavelengths. Aside from the feed and reflector configuration the system operates in a manner similar to that described under the amplitude sensing monopulse system. The two ganged coaxial probe monopulse organ pipe scanners provide the azimuthal scan and the appropriate monopulse RF components at the scanner combine the outputs so as to produce an elevation phase comparison monopulse system.

In the design of this system one of the important problems is, again, the aperture blocking problem. The two feeds which are placed at the respective foci of the two half-parabolic cylinder reflectors constitute the block. Furthermore, off-setting the feeds does not help this condition since it increases the separation between the reflectors and has a similar effect on the sum pattern as the aperture block — an increase in the sidelobe level. Using reflectors having short focal lengths so that the feed horns can be made smaller, and minimizing the spacing between the reflectors, appear to be only a partial solution to the problem.

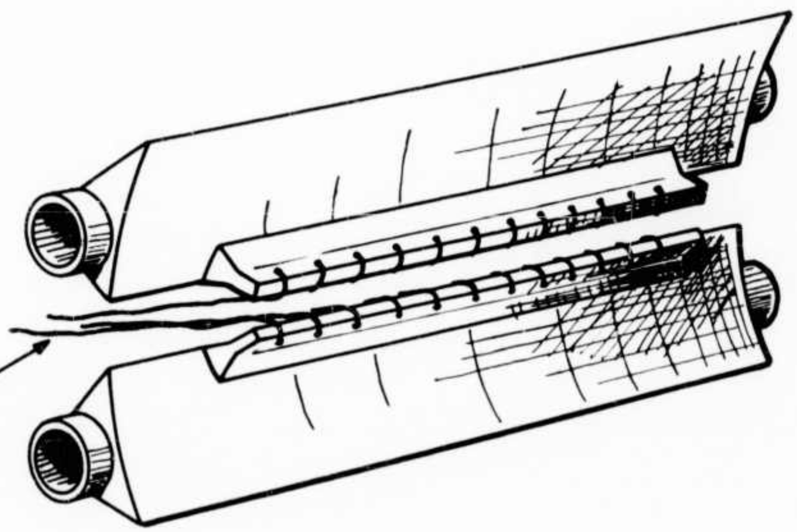


Figure 9-2. Possible Antenna Configuration for Phase Sensing Elevation Monopulse System

SECTION 10

DUAL TERMINAL ANTENNAS

The dual terminal antennas of interest in this particular section are dual terminal arrays which can be used either as primary sources for reflector type antennas or as direct-radiating aperture antennas. A dual terminal array consists of a linear array of discrete radiating elements coupled to a common transmission line or waveguide, which can be fed from either end. In the usual linear array the elements are fed in phase to produce a broadside pattern. This is accomplished by creating a 180-degree phase shift in the coupling of adjacent elements to the feed line, and by adjusting the inter-element spacing d so that $d = \lambda_g/2$ where λ_g is the wavelength in the feed line. However, by adjusting the spacing d so that

$$d = \frac{\lambda_g}{2} + \delta$$

where

$$\frac{\lambda_g}{2} >> |\delta| > 0$$

the radiation will depart slightly from the broadside condition. Under these assumptions, the patterns at the two ends of a dual terminal array in any plane containing the array will be mirror images of each other relative to the broadside plane. In the receive condition this antenna can be used as an accurate single antenna interferometer which will give angular information to a high degree of accuracy within a narrow sector without ambiguity. Its operation in this mode is analogous to a phase sensing monopulse system. The output of the two ends of the array are connected through equal lengths of transmission line to the isolated terminals of a hybrid. The sum port of the hybrid produces a power pattern of the array which consists of a broadside beam whose width is broader than that of the conventional single terminal broadside beam. As δ is increased this beam becomes broader until it splits into two beams symmetrically, located relative to the broadside plane. The difference port power pattern is characterized by a null in the broadside direction separating a pair of beams symmetrically placed on either side of the broadside plane. These beams are narrower than the sum port beam having the same δ. As δ increases, the null remains at broadside, but the peak of the two beams are spread farther apart. When $\delta = 0$ the power pattern reduces to zero for all directions.

The use of this technique with the MUBIS lens results in an accurate narrow beam in the plane of the array which can be scanned in the orthogonal plane by means of the MUBIS technique. Figure 10-1 shows a possible configuration for such a system. It consists of

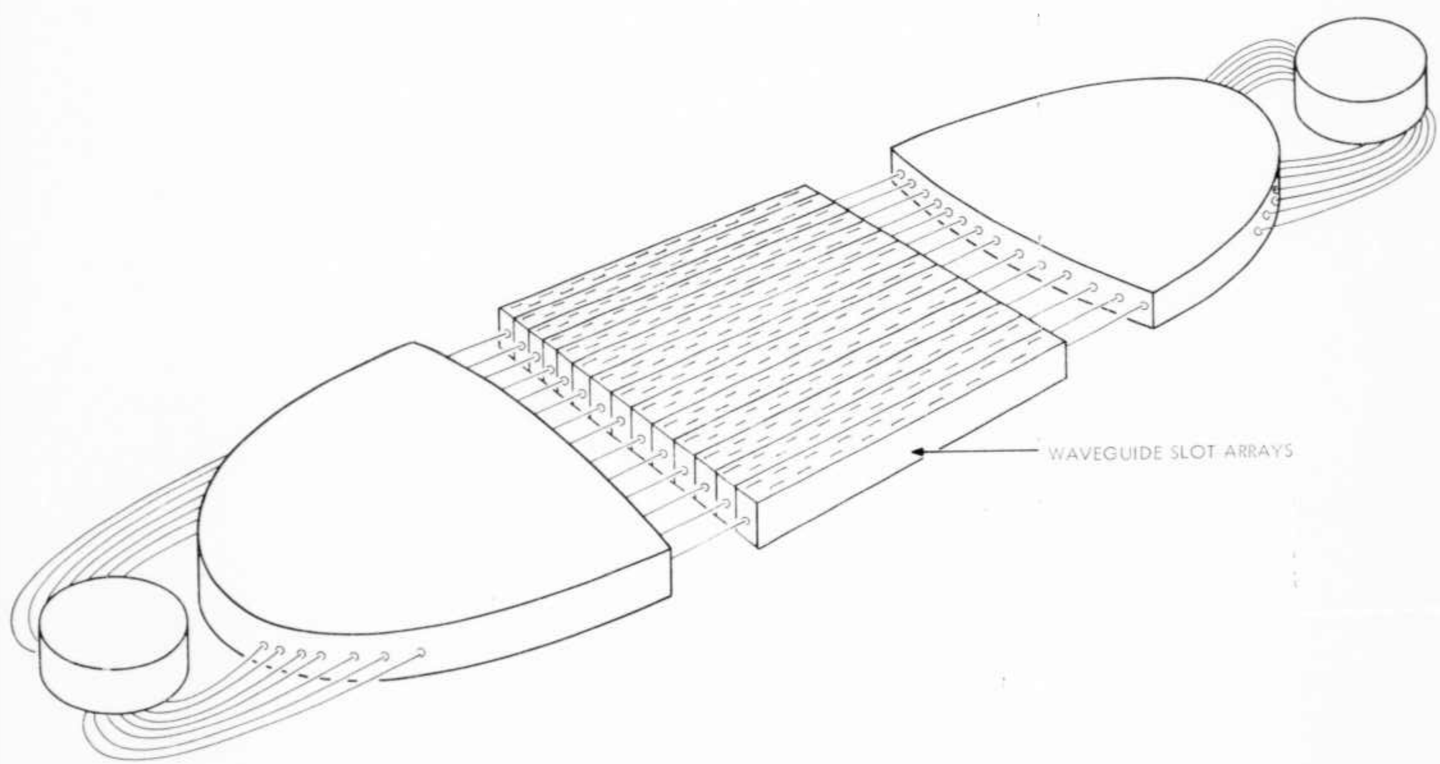


Figure 10-1. Dual Terminal Arrays Used in Combination with MUBIS

an array of dual terminals arrays. The constraining elements (coaxial cables) of one lens are each connected to the upper terminals of this two-dimensional array while the cables from another identical lens are connected to the respective lower terminals. Scanning in the MUBIS plane is accomplished by ganging the two organ pipe scanners as in the case of the dual lens monopulse system. Accurate angular information in the orthogonal plane is obtained by appropriately processing the outputs of the dual terminal array.

One of the principal objections to such a system is the very narrow sector covered in the plane orthogonal to the MUBIS plane. As an interferometer, however, it does have potential since it can be steered in one plane over a rather broad sector and it can be used as an accurate transit type of instrument in the orthogonal plane.

One of the major difficulties in implementing this system, however, is the problem associated with spacing the dual terminals arrays. This is a problem similar to that presented in the frequency scanning technique, Section 6.

10.1 DUAL TERMINAL ARRAYS AS PRIMARY SOURCES (Sletten Feed)

A dual terminal array, when used as a primary feed in conjunction with a parabolic reflector or a lens, exhibits certain useful characteristics. When feeding a reflector the extended array produces a series of defocused beams – the angular position of each beam in space being directly related to angular separation of each radiating element in the array, from the focus of the reflector. Therefore, when transmitting with the full array under single terminal operation (opposite terminal matched), the far field radiation pattern is a fan beam which consists of the envelope of the peaks of all these defocussed beams. In the receive case, however, under dual terminal operation, with separate detection at each terminal, the system behaves as two separate antennas. Each end of the dual terminal array has an associated far field phase and amplitude pattern. The amplitude patterns are almost identical while the phase pattern is different for the two ends of the array. This difference in phase function can be used as a measure of the angular position of the target in the fan beam. Such a system has been designed and built by AFCRL personnel for use with a parabolic torus. A single dual terminal antenna consisting of a waveguide slot array (commonly referred to as a Sletten Feed) has been used as the extended feed for producing a fan beam on transmit and for determining elevation targets on receive.

By placing the array of dual terminal antennas in the focal region of a half-parabolic cylinder, a scanning height finding antenna system can be effected. See Figure 10-2.

One of the problems associated with the design of such a system is a thorough quantitative knowledge of the behavior of the reflected waves in the focal region of the parabola is required. It is known that for a defocused antenna feed, the locus of best focus lies along a curve known as the caustic. However, in a parabola, this caustic curve depends on the angle of incidence of the incoming ray and also on the particular point

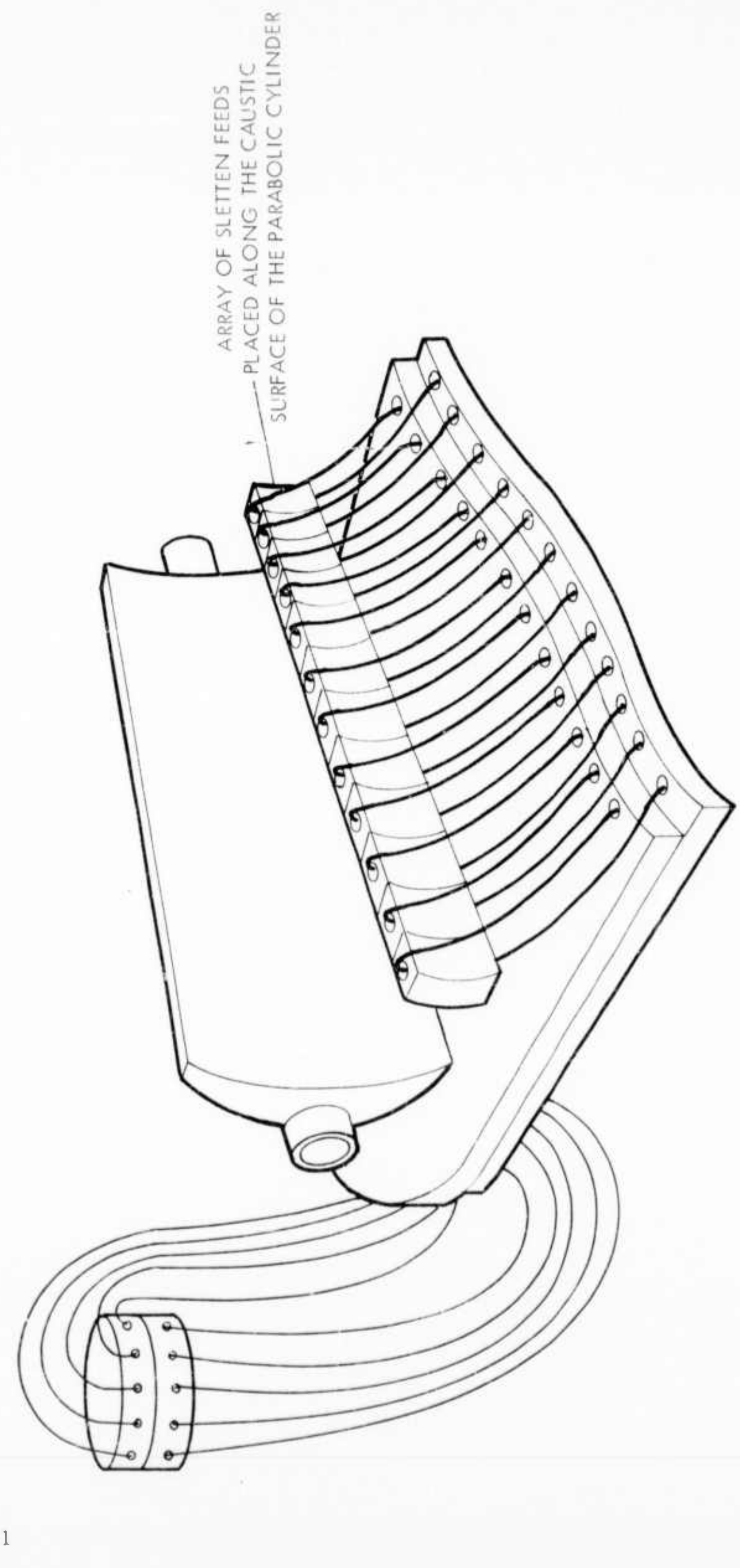


Figure 10-2. Sletten Feed Used with MUBIS

which the ray strikes the parabola. Since it is desirable when designing the feed that it be optimized within a given range of elevation angles, it becomes necessary to select a particular point on the reflector for which this feed will be optimum. This point is usually selected as the midpoint of the reflector. When designing the array, therefore, each element must be phased with respect to each other to focus the energy at this midpoint of the reflector. The usual problems associated with aperture blocking and inter-element spacing in the MUBIS scan plane also exist.

Nevertheless, it appears that this phase in space technique is worthy of research for supplementing the MUBIS technique in producing an antenna system capable of providing accurate angular information in two dimensions.

SECTION 11

MULTIPLE LENS SYSTEMS

The use of multiple lenses in a system for obtaining two-dimensional, angular information consists of arraying the line sources, either horizontally or vertically, whichever is desirable. The result is a two-dimensional, planar array in which scanning in one plane is accomplished by the scanners ganged together to scan in unison through their respective lenses. Scanning in the orthogonal plane is accomplished by properly phasing the inputs to the individual scanners to effect a phase taper in this orthogonal plane. Of the possible methods of accomplishing this, the use of waveguide phase shifters appears to be the most straightforward. This system also has the advantage of handling higher powers since the lens, the scanners, and the phase shifters can be made to handle high peak as well as average powers. At first glance, such a system does not appear to be very sophisticated since it represents the "brute force" approach to the two-dimensional scanning problem. However, this method offers a solution to the power problem without the complexity of the phased array system. The system could have a multiple beam capability in each plane by using more than one set of scanners at the focal arcs of the lenses. Each scanner set would have its own phase shifters so that independent control in both azimuth and elevation is possible.

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